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Environmental Change and Human Occupation of Southern Ethiopia and Northern Kenya during the last 20,000 years

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Abstract

Our understanding of the impact of climate-driven environmental change on prehistoric human populations is hampered by the scarcity of continuous paleoenvironmental records in the vicinity of archaeological sites. Here we compare a continuous paleoclimatic record of the last 20 ka before present from the Chew Bahir basin, southwest Ethiopia, with the available archaeological record of human presence in the region. The correlation of this record with orbitally-driven insolation variations suggests a complex nonlinear response of the environment to climate forcing, reflected in several long-term and short-term transitions between wet and dry conditions, resulting in abrupt changes between favorable and unfavorable living conditions for humans. Correlating the archaeological record in the surrounding region of the Chew Bahir basin, presumably including montane and lake-marginal refugia for human populations, with our climate record suggests a complex interplay between humans and their environment during the last 20 ka. The result may contribute to our understanding of how a dynamic environment may have impacted the adaptation and dispersal of early humans in eastern Africa.

Keywords: archeology; paleoclimate; African Humid Period; push factor; adaption; migration; hunter-gatherers; foragers; pastoralism; Chew Bahir

1 Introduction

Climatic change is broadly considered to be one of the major drivers for human migration including the dispersal of early modern humans (Beyin, 2011a; Rosenberg et al., 2011; Richter et al. 2012) and the shift from hunter-gatherers to pastoralism (Garcin et al., 2012; Lesur et al., 2014). However, it is not clear how far climate change has really affected human migration (e.g. Brandt et al., 2012) and how other factors, such as human agency, in the sense of individual self-determination and will, under the pervasive influence of culture, might have been involved (Ahearn, 2001; Dornan, 2002). The same issue applies to the role of climatic change for the emergence of technological and behavioral innovation (Ambrose et al., 1998; Garcin et al., 2012; Ziegler et al., 2013).

If climatic change is assumed to play an important role and the mode of climatic change could have controlled the way human populations responded to climatic variations, questions arise as to whether this depended on the duration and direction of transitional states. Furthermore, the question is whether short-term events or rather long-term gradual transitions were the relevant drivers. Finally, what type of climatic conditions are associated with human dispersal and whether abrupt changes to unfavorable conditions (e.g. towards increased aridity; deMenocal, 1995; Carto et al., 2009) may have triggered the migration of surviving populations to more favorable locations. Alternatively, a change towards favorable living conditions (e.g., a humid phase; Trauth et al., 2007; Kröpelin et al., 2008; Castañeda et al., 2009) may provide sufficient resources to allow the population to grow and subsequently disperse through otherwise ecologically critical zones into larger geographical space over several generations. The current debates on the way climate affects humans are hampered by the lack of continuous high-resolution terrestrial paleoenvironmental records in Eastern Africa (Brandt et al., 2012) and the limited availability of contemporaneous archaeological data of the same region (Basell et al., 2008; Leplongeon, 2014).

As a contribution to these discussions, we present a continuous high-resolution lacustrine record for the past 20 ka from Chew Bahir, a deep sedimentary basin in southwest Ethiopia. The record is correlated with the available archaeological record of human occupation in the region, as a way of evaluating the impact of different styles of climate change on local terrestrial ecosystems (including human societies) at various timescales (10^1–10^4 yrs). The evidence of human occupation is based on the variations in frequency of radiocarbon dates from archaeological sites in the SW Ethiopian highlands near the Chew Bahir basin and the shores of the lakes in the Main Ethiopian Rift (MER) and the Omo-Turkana basin (Fig. 1). The precipitation-rich highlands and these lakeshores are hypothesized to have been refugia and centers of innovation during times of climatic stress (Ambrose et al., 1998; Basell, 2008; Joordens et al., 2011; Brandt et al., 2012; Brandt and Hildebrand, 2005). The Chew Bahir basin, today a dried-out saline mudflat providing the climatic archive for our correlation, is situated in a biogeographically highly sensitive transition zone between the Main Ethiopian Rift and the Omo-Turkana basin where the fossils of the oldest known anatomically modern humans were found (e.g. Day and Stringer, 1991; McDougall et al., 2005; 2008; Sisk and Shea, 2008).

In order to evaluate how different rates of environmental change affected settlement pattern and cultural innovation for survival and adaptation, we test the extent to which gradual and rapid climatic events in the lacustrine sedimentary record are also expressed in the archaeological record of hypothesized refugia. Traditionally used for places where species survive during cold periods (López-Garcia et al., 2010), the term refugium is used here for areas that might have permitted the survival of human populations during arid phases. We have considered the period since 20 ka BP because it encompasses both, the highest archaeological data coverage for post Middle Stone age assemblages (Basell, 2008) as well as a detailed sedimentary record of dry-wet alternation within a full precessional cycle. This is a novel experiment to compare both the paleoclimatological and archeological evidence directly from the source area of modern humans to test current hypotheses about how climate affects humans. Due to the incompleteness of the archaeological data set, the results are of course very preliminary and hypothetical, but could be an important starting point for further research in this field.

2 Data and methods

2.1 Paleoclimatic reconstruction using continuous lacustrine sedimentary records

In a pilot study for the deep-drilling campaign within the 'Hominid Sites and Paleolakes Drilling Project' (HSPDP, http://hspdp.asu.edu/), six cores along a ~16 km long NW-SE transect across the Chew Bahir basin were collected during two consecutive drilling campaigns in 2009 and 2010. The cores were 9 to 19 m long, spanning the last ~60 ka, and were analyzed with respect to their geochemical, geophysical, biological, and sedimentological properties (Foerster et al., 2012; Foerster et al., 2014).

There are two age models for the environmental record of the Chew Bahir basin: (1) an age model based on six AMS ^{14}C ages of biogenic material from a single core (CB01) collected in 2009 and published in Foerster et al. (2012); (2) an age model based on 32 AMS ^{14}C ages of biogenic carbonate, fossilized charcoal and organic sediment from multiple cores (CB01, CB03–06) and published in Foerster et al. (2014) and Trauth et al. (2015). For the newer age model, the potassium records of cores CB03–06 were tuned to the potassium record of CB01, suing a minimum of tie-points, to construct a composite depth scale with the radiocarbon ages from all cores CB01, CB03–05 projected onto this depth scale (Suppl. Fig. 1). The age model, discussed in detail in Foerster et al. (2014) and Trauth et al. (2015), is considered to be statistically robust, even though it provides only a floating chronology for large portions of the sedimentary record. It is to be noted, although the newer age model is a lot more sophisticated, it does not much differ from the old age model published in Foerster et al. (2012) (Suppl. Fig. 2). All radiocarbon ages were calibrated with OxCal (Bronk Ramsey, 1995) using the IntCal13 calibration data set (Reimer et al., 2013). The weighted mean of the probability density function was used for the age model, which was constructed by linear interpolation between dated levels (Trauth et al., 2015). For the interpolation of all proxy records upon the age model the most reliable results were obtained by using a linear interpolation technique. We refrained from tuning our climate record to high-latitude records or other East African records. For the paleoclimate discussion of our interdisciplinary comparison, we use the CB01 record (Foerster et al., 2012), because it is the most complete record with the highest temporal resolution (~3–10 years) for the past 20 ka in the Chew Bahir basin. As already shown in Trauth et al. (2015) we use CB03 to fill the gap in CB01 between ~9.8 ka and ~9.1 ka BP, and also for the gap at the end of the Younger Dryas, ~14.8–14.9 ka BP and past ~0.8 ka (Fig. 2).

The proxy-climate record is based on potassium (K) abundance, previously established as a reliable proxy for aridity in the Chew Bahir cores (Foerster et al., 2012) (Fig. 2). Increased influx of K occurs during dry phases, due to enhanced activity of extensive, sparsely-vegetated alluvial fans fed by the potassium-rich gneisses and granites of the adjacent Hammar Range. During arid phases, when rainfall events are rare and short-lived, K, the weathering product of feldspar, feldsparthoids and mica with a high solubility and reactivity, is rapidly transported from the constrained source of the Hammar Range to the Chew Bahir basin. Furthermore, high occurrences of K have been shown to be linked to changes in the lake water chemistry, that in turn is controlled by variations in precipitation influx (Foerster et al., 2014). During the most arid phases, the paleolake is believed to have become completely desiccated, or at least strongly regressed with a very low biogenic productivity (Foerster et al., 2014). With the onset of greater, more evenly distributed rainfall during humid phases, an extensive (2,000 km^2) paleolake filled the basin with a maximal water depth of 50 m. Fluvial input increased and a dense vegetation cover that must be assumed for phases of increased humidity (e.g. Mohammed and Bonnefille, 1998; Dupont et al., 2000; Umer et al., 2007) on the slopes of the Rift flanks most likely constrained the influence of the alluvial fans off the Hammar Range, which represents the major source of the K-rich minerals. Other proxies support this interpretation: the diatom stratigraphy indicates that freshwater conditions prevailed during long, stable humid phases (Foerster et al., 2014). These data, taken together with lake-level reconstructions from Lake Turkana (e.g. Johnson et al., 1991; Brown and Fuller, 2008; Garcin et al., 2012) and Lake Ziway-Shala (Gillespie et al., 1983) give an indication of the immense environmental impact of the major climatic fluctuations, especially the dry intervals that punctuate the early-mid Holocene African Humid Period (AHP, ca. 15–5 ka BP) (Suppl. Fig. 3).

2.2 Evidence of human occupation by radiocarbon date frequency

The regional and chronological distribution of archaeological sites may not be a direct indicator of settlement intensities, as it is influenced by a number of external factors. The method of using radiocarbon frequency to infer human presence and mobility has its limitations due to the presence of gaps during certain phases, that connote human absence in the area, but do not prove that humans were definitely not present during that time; the evidence of their presence may not have yet been recovered, or, also possible, was not preserved. The accessibility of the area has a clear influence on the research activities and therewith on the number of yet undiscovered sites and, consequently, the number of derived ages. Preservation conditions of datable organic material under changing climatic conditions contribute to the availability of radiocarbon dates, which also include the undocumented removal of finds by natural (degradation, inundation, erosion etc.) as well as anthropogenic forces.

However, keeping these caveats in mind, and considering that this is the only available approach to determine the settlement intensity in the area, the frequency of radiocarbon dates from archaeological sites nevertheless provides a valuable indication of changing settlement patterns, allowing inferences about where, when and, at best, how far humans were influenced by climatic conditions: Increased human occupation should give rise to a higher archaeological visibility. Human occupation is presented here using the radiocarbon date frequency from two documented ecologically favorable zones in close proximity to our climate record; the precipitation-rich highlands and around the shorelines of nearby lakes (Fig.1).

Specifically, our initial archaeological dataset is comprised of 26 radiocarbon dates from the SW Ethiopian highlands predominately from two research projects; the Kaffa Archaeological Project (sites are located between 1370 and 2260 m a.s.l.; Hildebrand et al., 2010; Hildebrand and Brandt, 2010) and the excavations at Mochena Borago rock shelter (2230 m a.s.l.; Brandt et al., 2012; Gutherz et al., 2002) (Suppl. Table 1). Due to the close proximity of these sites to the Chew Bahir catchment, climatic shifts of the highland region should be visible in the sedimentary record of the basin. Similarly, we would expect to find an expression of climatic extremes in the settlement activities of the probable highland refugia for the last dry-wet cycle (Fig. 1). A second dataset, the lake refugia dataset, comprises 31 radiocarbon dates from Lake Turkana and 6 dates from the Ziway-Shalla basin, which are hypothesized to have served as retreat areas for humans during times of climatic stress (Basell, 2008; Joordens et al., 2011) (Suppl. Table 1).

In order to ensure a consistent age scale, we used conventional radiocarbon ages and calibrated them using CalPal (version April 2013, Weninger and Jöris, 2008) with the IntCal13 calibration curve (Reimer et al., 2013). All ages were calibrated using the 2-sigma standard deviation. Age dates from bone apatite were excluded because of their large uncertainties.

3 Results and Interpretation

3.1 Climatic change and phases of climatic stress

The climatic record of the Chew Bahir basin, represented here by the variability in K as an indicator for a dry climate, shows that the moisture availability has been subject to dramatic fluctuations on time scales ranging from 10^4 to 10^1 years, with either relative abrupt or gradual transitions between dry and wet conditions (Fig. 2). Extreme dry conditions in the Chew Bahir basin prevailed prior to ~15 ka BP and were interrupted by short-term wet-spells of 200–500 year duration (Foerster et al., 2012). From 15 ka onwards an abrupt change towards extremely humid conditions during the African Humid Period (AHP, 15–5 ka BP) occurred, which was the consequence of a precession-controlled Northern Hemisphere (NH) insolation maximum (e.g. Foerster et al., 2012; Junginger and Trauth, 2013). The observed climate transition has caused a marked environmental transformation from unstable dry conditions to relatively stable humid conditions, which resulted in the establishment of large fresh water lakes and the development of a lush vegetation cover. Despite the high moisture availability, several short-term drought events interrupted this humid period. For instance, between 14.2–13.5 ka, an event related with the Older Dryas stadial (OD, ~14 ka, Stager et al., 2002) eventually caused the return to dry conditions immediately after the relatively abrupt onset of the AHP. Another major dry spell occurred between ~12.8–11.6 ka that correlates with the well known NH Younger Dryas stadial (YD, Foerster et al., 2012) and is expressed in the Chew Bahir record as an abrupt return to aridity, comparable to the conditions during the Last Glacial Maximum (LGM) has caused the complete desiccation of paleolake Chew Bahir. This arid episode is documented in many sites in Africa north of 10°S (e.g. Barker et al., 2004; Brown et al., 2007; Tierney et al., 2011; Junginger et al., 2014). The transition from the YD to the relatively stable humid climate of the early and mid-Holocene was relatively fast, probably within ±200 years. As the climate proxies and fossil records of the basin suggests, this rapidly-changing environment culminated in the development of an extensive (2,000 km^2), nutrient-rich freshwater lake, at least 50 m deep, with abundant fish and surrounded by dense vegetation. This paleolake Chew Bahir overflowed into the Omo-Turkana basin during high stands (Grove et al., 1975; Junginger and Trauth, 2013).

Other arid excursions during the AHP with moisture fluctuations are observed at ~10.5, ~9.5, 8.15–7.8 and ~7 ka BP which were not thought to have resulted in a complete desiccation of the paleolake and disappearance of the surrounding vegetation (Foerster et al., 2012). The most pronounced arid excursion, dated here at ~7.8 ka BP, would have affected the environment considerably, but would not have resulted in a complete lake regression or vegetation change, possibly allowing human populations to persist in the area, despite droughts that continued for several centuries. This interpretation is supported by lake-level reconstructions of nearby paleolakes Turkana and Suguta (Garcin et al., 2012; Junginger et al., 2013), that also show several excursions to arid conditions during the AHP lake interval. The dry spell at ~7.8 ka BP was preceded by a gradual ~1,000 year-long moisture reduction, which has been also observed at many other low-latitude sites (e.g. Fleitmann et al., 2003, Dykoski et al., 2005; Gupta et al., 2005; Weldeab et al., 2007), and is assumed to have led into the 8.2 ka cold event observed in the NH (Benson et al., 1997). In southern Ethiopia the humid conditions of the AHP gradually declined from ~6.5 ka to ~5 ka, punctuated by several 80–20 year-long dry events (Trauth et al., 2015). Arid conditions have persisted since then, interrupted only by a short-lived event of higher moisture availability at ~3 ka BP and a distinct phase of wet conditions between ~2.2–1.3 ka BP.

3.2 Human occupation in a changing environment

Although derived from a sparse archaeological dataset, the frequency distribution of radiocarbon dates over the past 20 ka contains distinct patterns of human occupation, including episodes of human settlement, interrupted by periods without such activity. The record of radiocarbon dates demonstrates that the oldest evidence for human occupation in that time interval is at two brief episodes between ~14.0–13.7 and ~13.4–13.2 ka BP, documented from sites in the Ziway-Shalla basin (Ménard et al., 2014). During the AHP highstands this basin hosted a paleolake up to 120 m deep, which has formed by the merging of the MER lakes Abiyata, Langano, Ziway and Shalla (Gillespie et al., 1983). The interval of ~14–13.2 ka BP may coincide with the high-latitude OD climatic event (Stager et al., 2002), recorded in Chew Bahir as a ~700 year-long drier episode after the abrupt onset of the AHP. The sites where the MER artefacts were found are situated between Lake Ziway and Abiyata-Langano, which implies that during this dry episode the lake level had been reduced to a level where settlement between the lake systems was possible. As these settlement activities coincide with a short phase of drier conditions, lake regressions and deterioration of water quality, this region can also be interpreted as a (lake) refugia. Human occupation is also identified at ~13.9 ka BP in the SW Ethiopian highlands. Generally, no evidence for occupation is apparent before this interval, probably because of the extremely dry LGM conditions (Gasse, 2000) that could have made the area mostly uninhabitable, although it is not sure whether the SW Ethiopian highlands were also entirely abandoned and where humans were during this interval. In general, a strong hiatus on archaeological record during the period exists between 30 to 15 ka BP, presumably superimposed by the prevailing dry conditions (e.g. Leplongeon, 2014; Pleurdeau et al., 2014). At the onset of the AHP, living conditions greatly improved with significantly increased moisture availability as documented in the climate record of Chew Bahir and the abrupt and rapid development of large lakes in the area (e.g. Junginger et al., 2013) (Fig. 2).

Evidence for human activity follows at the northeastern shore of paleolake Turkana between ~11.5 and 9.2 ka BP. Due to the contrasting reconstructions of the lake levels of paleolake Turkana that are based on non-continuous and/or different proxy data sets (Johnson et al., 1991; Brown and Fuller, 2008; Garcin et al., 2012; Bloszies et al., 2015) it is not clear though whether the level of paleolake Turkana has fluctuated repeatedly by 50 m during this interval or it may have fallen gradually by 20 m between ~10.8–10 ka BP. After the pronounced dry phase of the Younger Dryas, lasting for about 1,200 years, all rift lakes including the Chew Bahir and Lake Turkana rapidly re-filled. Two archaeological sites at the northeastern shore (Fig.1; FxJj 12 and GaJi 11; Owen et al., 1982) are situated almost at the highest shoreline of the paleolake, right at the river that connected the Chew Bahir with the Turkana basin during overflow times. Assuming occupation along the lake shore at ~11.5–9.2 ka BP, there was probably an additional (third) rainy season in August-September, between the regular spring and autumn rainy seasons linked to the insolation maximum at the equator. This additional rainy season would have resulted in almost continuous rainfall from April to November (Junginger and Trauth, 2013; Junginger et al., 2014). Lake-level records indicate that this extra rainy season may have been unstable, causing pronounced fluctuations in the water budget of the lakes (Junginger et al., 2014). The apparent break in the occupation record after ~9.2 ka could be explained by the highly fluctuating lake levels, simply washing away all archaeological evidence. It is also possible that the lake-marginal environment was unfavorable for occupation during periods of high rainfall, when relatively dense woody vegetation would have made hunting more difficult and could have favored the spread of diseases.

The evidence for human occupation in the SW Ethiopian highlands during the AHP is particularly noteworthy: here, several short-term occupation episodes are dated at ~10.5–10.2 ka BP, ~9.5–9.3 ka BP, ~8.0–7.8 ka BP and ~7.0–6.5 ka BP. These intervals coincide (within the dating errors) with short-term events of pronounced aridity punctuating the AHP. These climatic events are found in the Chew Bahir record, and also in both paleolakes Turkana and Suguta, where lake regression and a rapidly-changing environment would have been accompanied by marked deterioration in water quality. Paleolake Chew Bahir would have been increasingly saline and alkaline, probably similar to Lake Turkana today (e.g. Odada et al., 2003).

The short-term changes in moisture availability during the AHP may have been driven by variations in solar irradiance due to varying numbers of sunspots (Solanki, et al., 2004; Junginger et al., 2014). These solar variations are assumed to have caused the absence of the third rainy season in August-September as well as attenuation of the other two wet seasons, as documented in the records of many basins from the Victoria basin along the East African Rift to Oman (e.g. Burns et al., 1998; Neff et al., 2001; Stager et al., 2002). This caused short-term episodes of pronounced aridity within a few decades, which caused unfavorable conditions for humans in large parts of the lowlands. As the radiocarbon frequency record suggests, the SW Ethiopian highlands seem to have served as a refugium during these episodes with increased environmental stress, on decadal to millennial time scales during otherwise long-term favorable conditions. Although the dates are too few for a reliable interpretation, and also the limited dating precision is a problem, the striking correlation of settlement episodes in the highlands with the occurrence of a series of pronounced aridity events at least deserves further research, specifically on the locations of human occupation during more favorable climate conditions. To date, our correlation suggests that a wetter climate punctuated by a series of droughts is reflected by multiple phases of increased settlement activity in areas that might have been used as refugia, most likely by short-term vertical migration of mobile hunter-gatherers. We thus carefully interpret the correlation between pulsed aridity and occupation of a hypothesized retreat area as the result of drought as a push-factor for a refugium-directed movement that would have otherwise been against the preference of hunter-gatherers.

At the onset of the >1,500 year-long Mid Holocene aridification trend (~6.5–5 ka), there is a striking coincidence between moisture decrease and colonization of the lake basins and the highlands. It is very likely that this movement was even further pushed by the series of short drought events, 20–80 years long, previously described by Trauth et al. (2015). These, at least 19 events of extreme aridity, punctuating the gradual transition to present-day arid conditions, are presumed to have had considerable effect on humans and may have contributed to the climate-driven cultural change presented hereafter. Between ~4.5 and 2 ka BP, extreme aridity could have ended habitation even in the two ecologically-favored regions; where human populations survived afterwards is still an open question. The Chew Bahir climate record suggests that aridity reached a level where lakes became highly saline and alkaline, rivers dried up, and the vegetation cover diminished in conditions of sparse, irregularly distributed rainfall. There is a significant discontinuity in the record of human occupation over the same interval, which could imply that movement to nearby refugia was an inadequate strategy for survival, and mortality was high throughout the region, with survivors dispersed to more distant regions. Renewed human occupation of both the lake and montane refugia occurred only during the inferred moisture increase at around ~2 ka BP, accompanied by an amelioration of living conditions (see Suppl. Table 1) (Fig. 2).

4 Discussion

4.1 Indications of climate-driven cultural change

The environmental shifts recorded in the Chew Bahir sediments most likely influenced the living conditions of prehistoric humans. One possible impact of these shifts are variations in the human occupation of the area, as we have derived it from the presence or absence of archaeological data during certain periods, particularly during the period before 15 ka ago (e.g. Pleurdeau et al., 2014). Some human populations may not have survived aridity; others would have adopted novel or modified subsistence strategies. Garcin et al. (2012) interpreted the chronological synchronism of low lake levels and the emergence of pastoralism in the Turkana Lake region in a similar manner. Wright et al. (2015) have recently suggested that this climate transition in the Turkana basin has caused for the transition from foraging to food production. However, a simplistic model of cause and effect between environmental parameters and human behavior is an inadequate conception of their complex interplay. Examples of economic transformations from other regions, such as northern Africa (e.g. Manning and Timpson, 2014), show that external conditions reduce the range of possible developments, while socio-cultural conditions favor particular concepts (Keding, 2009; Vogelsang and Keding, 2013). In addition, further incalculable factors, which may be summarized under the ambiguous term of ‘human agency’ play a determining role in the human decision making (Dobres and Robb, 2000). The role of individuals as active social agents is, however, hardly detectable in the archaeological material.

Despite their proximity, cultural development in the Ethiopian highlands, and lakes and their marginal lands differ considerably. At Lake Turkana, early pottery is found at forager sites as early as ~10 ka BP. Diagnostic features of these sites are fisher-hunter-gatherer subsistence, heavily relying on aquatic resources and restricted residential mobility. This lifestyle and its diagnostic artefacts, such as wavy-line pottery and harpoons (Phillipson, 1977; Barthelme, 1985) link these sites with assemblages from the southern Sahara, which are grouped under the term ‘African Aqualithic’ (Sutton, 1977) or ‘Khartoum Horizon Style’ (Hays, 1971). However, the dating of the Turkana sites is problematic. Most early dates were measured on bone apatite, and were therefore considered unreliable and, hence, were not included in our dataset (Fig. 2). Despite these dating problems, it is widely accepted that pottery was already produced in the area before early domesticates arrived. The diagnostic decorated sherds can be assigned to the eastern facies of the wavy line group, which is distributed over a large area in northeastern Africa between ~11 and ~7 ka BP (Jesse, 2003, Tab. 61, Tab.62, p.283 ff.).

The beginning of herding in the Turkana region, at around 4 ka BP, is contemporaneous with the construction of megalithic pillar sites and with the earliest secure dates for Nderit pottery (Hildebrand and Grillo, 2012). In contrast, domesticates and pottery do not appear in combination in the SW Ethiopian highlands until about 2,000 years later (Lesur-Gebremariam, 2009; Hildebrand et al. 2010; Lesur et al., 2014). Preliminary occupation of the highlands is characterized by highly-mobile, unspecialized hunter-gatherer groups, which exploited a broad spectrum of resources in an opportunistic way (Lesur et al., 2007). This contrasts with the social organization of more complex hunter-gatherers, identifiable by sedentism or substantially restricted residential mobility, and a ‘focal exploitation of a particular resource (commonly fish)’ (Kelly, 1995, 302). The lake environment of Lake Turkana may have fostered the emergence of such complex hunter-gatherer groups. Further characteristics of such groups are ownership of resources, a more formal leadership and an erosion of egalitarian ideology (Kelly, 1995, 302; Zvelebil, 1998, 8). Such attributes of a socio-economic pre-adaptation to a food-producing economy might have facilitated a subsistence change in the Turkana region.

Nevertheless, the chronological difference of 2,000 years between the earliest evidence of domestic animals in the Lake Turkana region and the southwest Ethiopian highlands has implications for the refugium hypothesis. If pastoral people retreated to the highlands during arid phases, they also changed their subsistence to a hunting and gathering way of life. Alternatively, settlement activities in the highlands were exclusively by local, possibly marginalized hunter-gatherer groups until 2,000 years ago. There is ethnographic and archaeological evidence for both scenarios, which shows once more that the strict classification into foraging or food-producing societies, is an over-simplification of a very complex and alterable situation (e.g. Smith, 1998; Kusimba, 2005).

4.2 Adaptation as a matter of timescale

An important aspect that has to be considered here, is the time scale on which climate is changing. Assuming the climatic record of the Chew Bahir basin reflects prevailing wet conditions between ~15 ka and ~5 ka BP, punctuated by several pronounced dry spells (~14.2-13.5 ka BP, around ~10.5 and ~9.5 ka BP, between 8.15 and 7.8 and at ~7 ka BP), causing a rapid change of the habitat with strongly regressed and increasingly alkaline and saline lakes and a sparse vegetation cover, hunter-gatherers were forced to expeditiously find alternative subsistence strategies. Such short-term solutions may be reflected in the higher frequency of dated settlements in the highlands during arid spells, which is interpreted as vertical migration of hunter-gather groups into more favorable environments. The change from a foraging subsistence to a productive mode of economy is intrinsically tied to changes in the social structure and ideology of the society (Vogelsang and Keding, 2013, 56ff.). Consequently, it is implausible that an abrupt transition of 50 years or even less might have triggered such a fundamental transformation. In contrast, the gradual and more than 1,500-year-long transition from wet to dry characterizing the end of the AHP in the Chew Bahir record could indeed have fostered an important socio-economic transition.

5 Conclusions

A 20 ka long paleoclimate record from the Chew Bahir basin in southwest Ethiopia shows both orbitally-driven long-term transitions from favorable to unfavorable living conditions, including several and short abrupt excursions towards drier or wetter episodes. The history of Chew Bahir is important in this context in providing a high resolution and continuous climate record rather than providing archaeological data which are not available for the studied timeframe (nor beyond), and is not within the scope of this study. The comparison of prehistoric settlement activities in the surrounding potential refugia, indicated by radiocarbon date frequency distribution with important events of climate stress indicates a significant correlation of short dry events with population movements into refugia, particularly the Southwest Ethiopian Highlands. Long-term climatic deterioration seemed to have caused large-scale migration. An adaption to a changing environment by changing the subsistence strategy is sometimes assumed to be the beginning of herding in the Late Holocene period and can only be a long-term process, eventually caused by long-term climatic shifts. However, the comparison of the climate and archaeological history indicates that not all climatic stress events correlate with increased occupation of refugia. Despite all data limitations, this suggests that external environmental factors merely reduce the range of possible developments, while socio-cultural conditions favor particular concepts. Further incalculable factors play a role and human behavior has not been entirely climatically triggered. This concept of decision-making within certain environmental boundaries, the 'human agency', has a crucial influence on the final development of culture as well as on societal decisions about the timing and direction of mobility.

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Figure Captions

Figure 1 | Setting of the Chew Bahir basin and archaeological sites in potential refugia. Archaeological sites are indicated by colored circles and numbers, that correspond to site names and numbers in Supplementary Table 1, to provide complete sample ID and cultural association. The pink circle marks the site of the Chew Bahir record. Climate diagrams represent monthly temperature means in deg C and precipitation in mm/month (IRI, last accessed 2/2014). Photographs from top: **(1)** Mochena Borago rock shelter in the SW Ethiopian highlands; **(2)** mudflats of the Chew Bahir basin, with the Hammar range in the background; **(3)** aerial shot of Lake Turkana, NE shore.

Figure 2 | Comparison of **(A)** the 20 ka Chew Bahir climatic record (K content as a proxy for aridity) and the variations with the earth's precession (Berger and Loutre, 1991) with **(B)** settlement in the SW Ethiopian Highlands and around lake margins (Turkana and Ziway-Shalla lakes). Climatic events: AHP - African Humid Period (~15-5 ka BP), YD - Younger Dryas (~12.8 -11.6 ka BP), OD - Older Dryas (around 14 ka BP), H1 - Heinrich event 1 (around 16 ka BP), LGM - Last Glacial Maximum (~24-18 ka BP). During the AHP, several pronounced dry spells occur, modulating the wet phase; the gradual Holocene aridification (orange bar) is punctuated by arid events on a decadal timescale (Trauth et al., 2015). Settlement activities in both potential refugia are indicated by radiocarbon frequency of archaeological finds, as listed in Suppl. Table 1. Cultural innovation is indicated by first documented wavy-line pottery (pot symbol) and the introduction of pastoralism (cow symbol); red or green colors refer to SW highlands or lake margins respectively. The green star signifies culture-related evidence of occupation that is not clearly datable.

Supplementary Table 1 | Radiocarbon dates from archaeological sites discussed in the text.

Supplementary Figure 1 | Intra-basin core correlation of Chew Bahir transect cores. **(A)** Standardized potassium records of the Chew Bahir transect cores tuned to the depth of CB-01. Red circles indicate the minimum number of tie points. **(B)** All potassium records were tuned to the composite age model based on cal. ^{14}C ages, indicated by black circles (modified after Foerster, 2014).

Supplementary Figure 2 | The composite age model of the Chew Bahir basin (Foerster et al., 2012, 2014; Trauth et al., 2015) showing a linearly interpolated vs. a cubic-spline age model, based on 32 AMS ^{14}C ages from Chew Bahir cores CB01, CB03–06. All radiocarbon ages were converted to calibrated ages with OxCAL, using the IntCal13 calibration curves (Bronk Ramsey, 1995, 2009a,b; Reimer et al., 2013). Ages are the weighted mean of the probability density function. The grey linear age model refers to the first simplistic age-depth model as shown in Foerster et al. (2012). **(A)** ^{14}C ages per tuned CB sediment cores. **(B)** Material used for age determination.

Supplementary Figure 3 | Potassium (K) content of Chew Bahir cores CB-01 (basin margin), CB-03 (transition), CB-05 (basin center) for the last 20 ka BP. Dashed lines refers to the African Humid Period (~15–5 kyr BP, AHP), grey bars mark arid phases during the Younger Dryas (YD) and the Older Dryas (OD) stadials as well as during the Last Glacial Maximum (LGM). Age control along the Chew Bahir record is shown as grey squares (radiocarbon ages) and red triangles (CB correlation tie points). The CB records are compared to the earth's precession cycle (Berger and Loutre, 1991), lake-level fluctuations for Ziway–Shala from Gillespie et al. (1983) and Turkana from Garcin et al. (2012; filled curve), Johnson et al. (1991; dotted curve), and Brown and Fuller (2008; dashed curve).

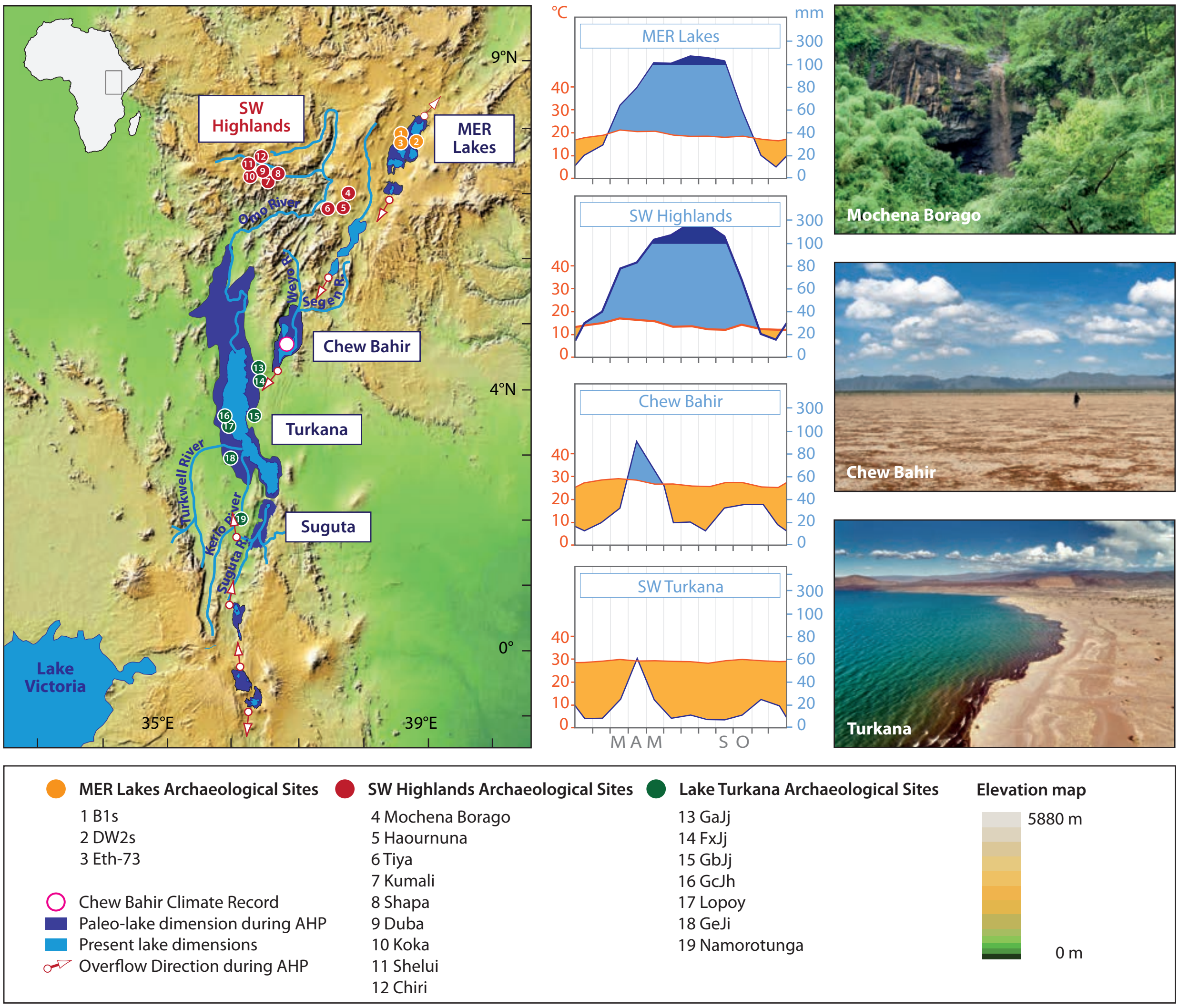
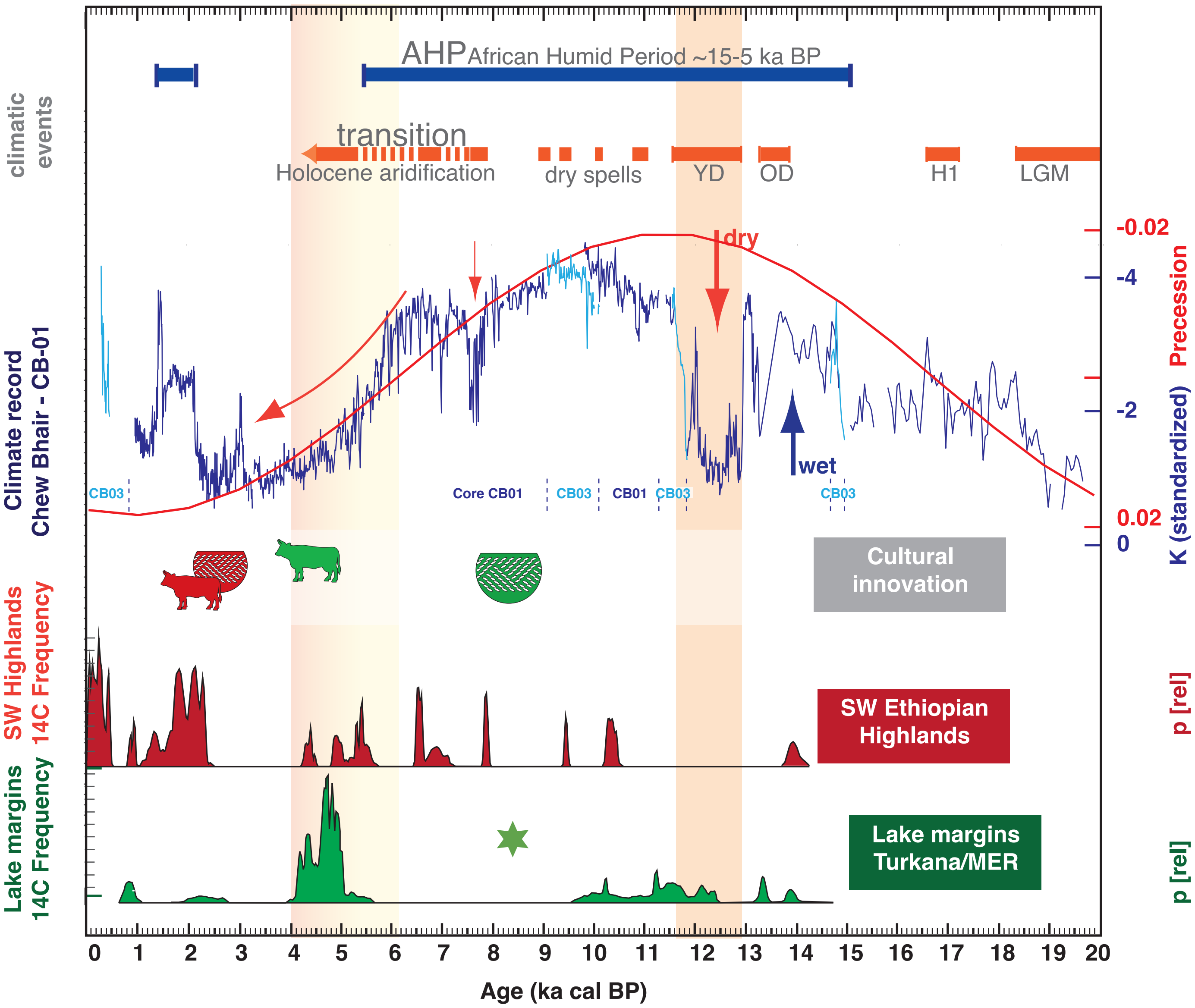
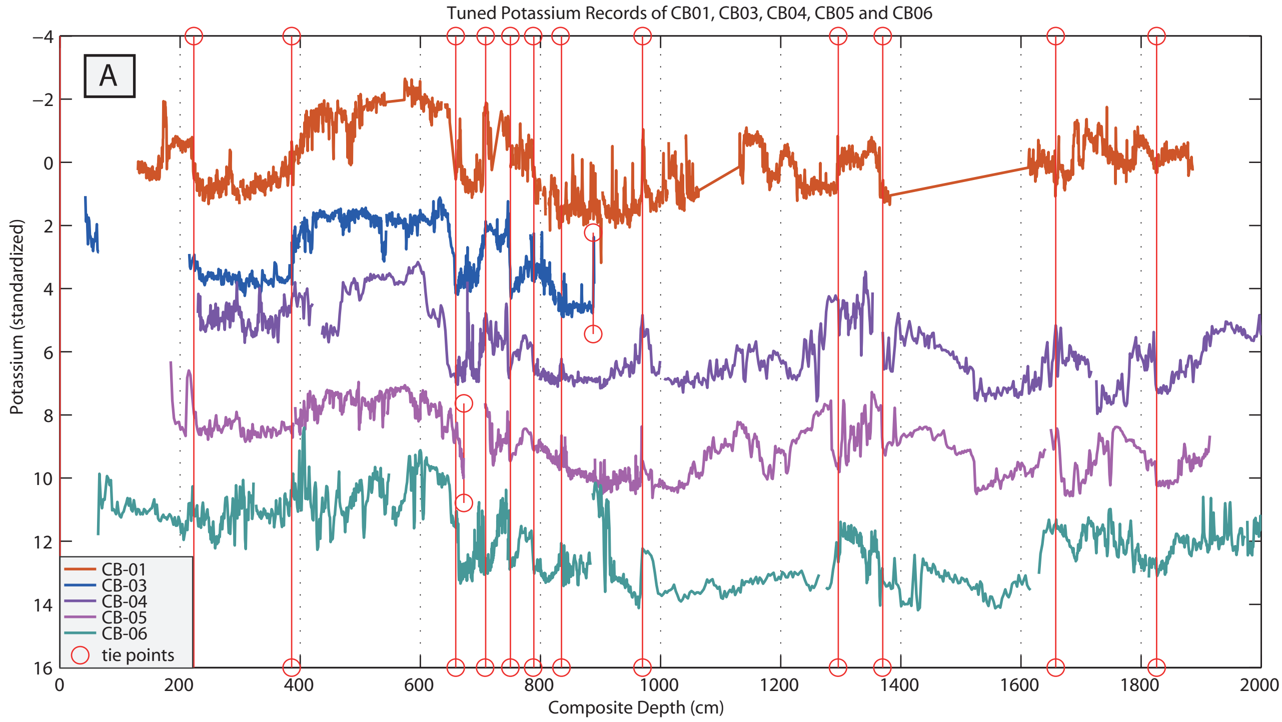

SW Highlands
MER Lakes
Chew Bahir
Turkana
Suguta
Lake Victoria
Omo River
Weyto R.
Segen R.
Turkwell River
Kerio River
Suguta R.
9°N
4°N
0°
35°E
39°E
°C
mm
MER Lakes
SW Highlands
Chew Bahir
SW Turkana
M A M
S O
Mochena Borago
Chew Bahir
Turkana
MER Lakes Archaeological Sites
1 B1s
2 DW2s
3 Eth-73
Chew Bahir Climate Record
Paleo-lake dimension during AHP
Present lake dimensions
Overflow Direction during AHP
SW Highlands Archaeological Sites
4 Mochena Borago
5 Haournuna
6 Tiya
7 Kumali
8 Shapa
9 Duba
10 Koka
11 Shelui
12 Chiri
Lake Turkana Archaeological Sites
13 GaJj
14 FxJj
15 GbJj
16 GcJh
17 Lopoy
18 GeJi
19 Namorotunga
Elevation map
5880 m
0 m

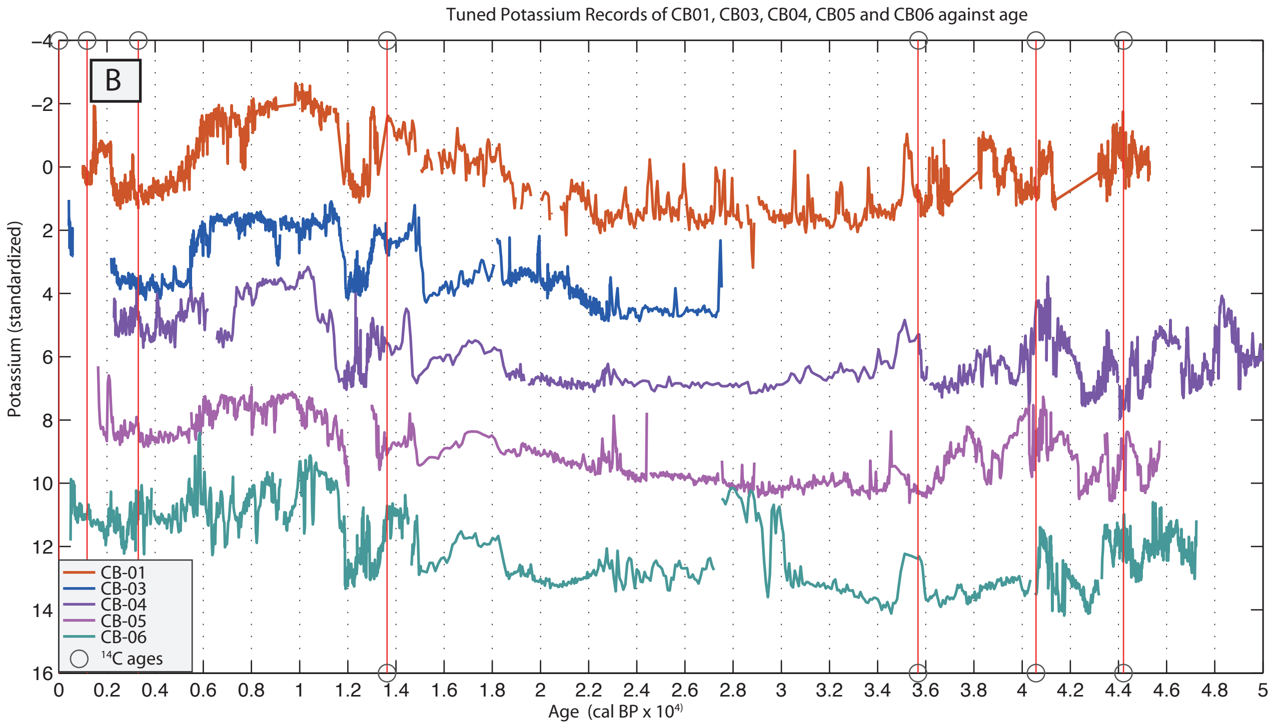
Figure 1



climatic events
AHP African Humid Period ~15-5 ka BP
transition
Holocene aridification
dry spells
YD
OD
H1
LGM
dry
wet
-0.02
-4
-2
0.02
0
Precession
K (standardized)
Climate record Chew Bhair - CB-01
CB03
Core CB01
CB03
CB01
CB03
CB03
Cultural innovation
SW Highlands 14C Frequency
SW Ethiopian Highlands
p [rel]
Lake margins 14C Frequency
Lake margins Turkana/MER
p [rel]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Age (ka cal BP)

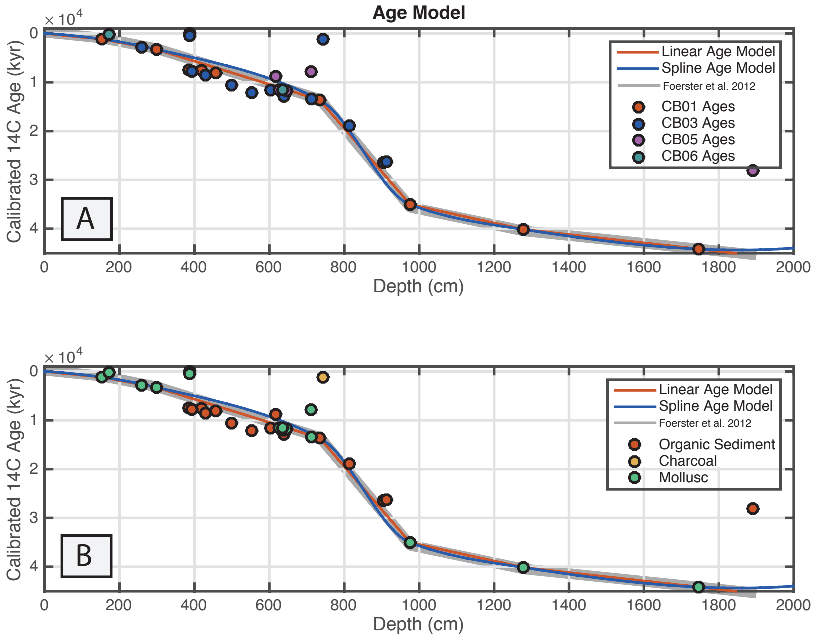
Figure 2





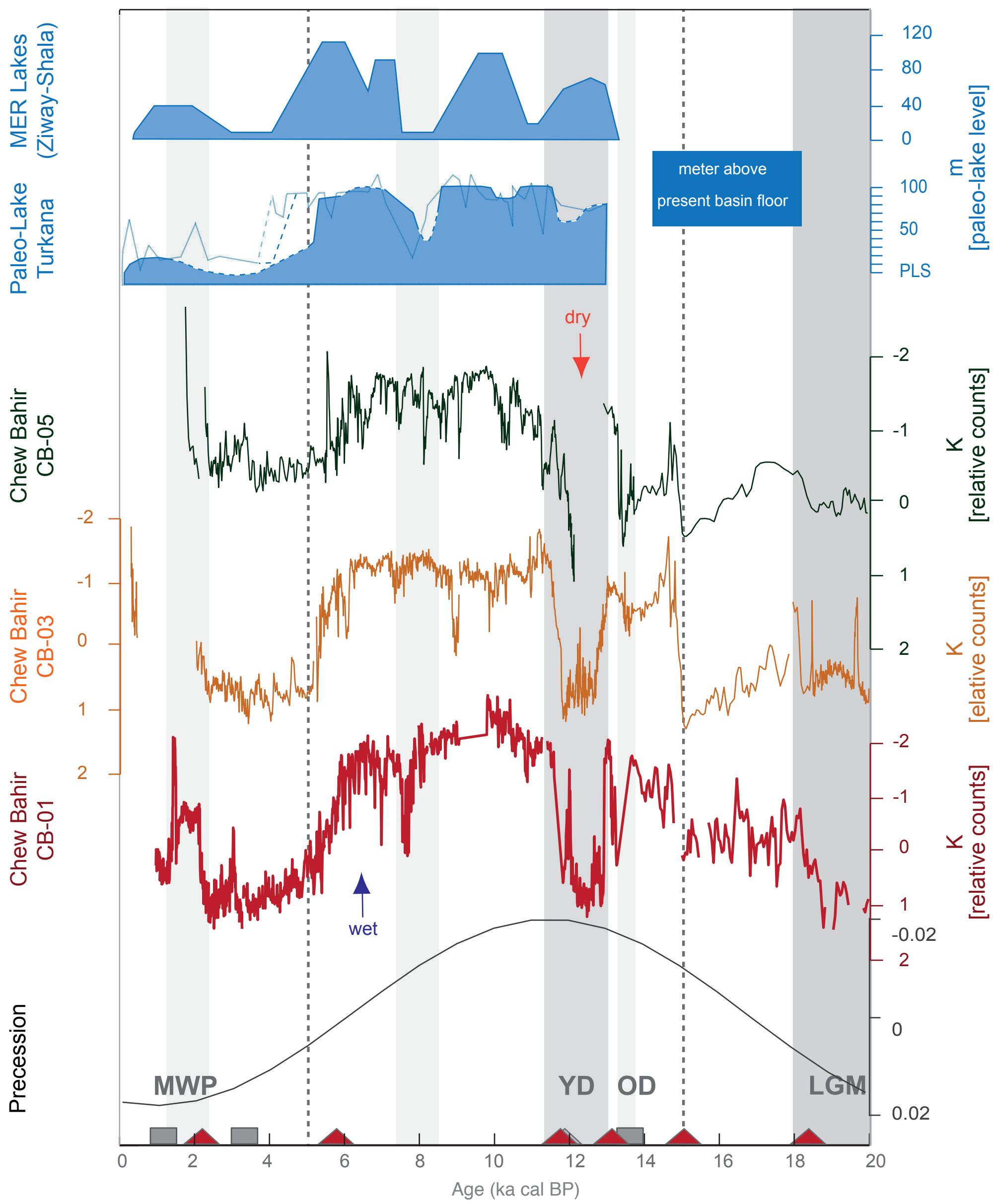
Foerster et al., Supplementary Figure 1

Supplementary Figure 1 I Intra-basin core correlation of Chew Bahir transect cores. **(A)** Standardized potassium records of the Chew Bahir transect cores tuned to the depth of CB-01. Red circles indicate the minimum number of tie points. **(B)** All potassium records were tuned to the composite age model based on cal. ^{14}C ages, indicated by black circles (modified after Foerster, 2014).



Foerster et al., Supplementary Figure 2

Supplementary Figure 2 I The composite age model of the Chew Bahir basin (Foerster et al., 2012, 2014, Trauth et al., 2015) showing a linearly interpolated vs. a cubic-spline age model, based on 32 AMS ^{14}C ages from Chew Bahir cores CB01, 03–06. All radiocarbon ages were converted to calibrated ages with OxCAL, using the IntCal13 calibration curves (Bronk Ramsey, 1995, 2009a,b; Reimer et al., 2013). Ages are the weighted mean of the probability density function. The grey linear age model refers to the first simplistic age-depth model as shown in Foerster et al., (2012). **(A)** ^{14}C ages per tuned CB sediment cores. **(B)** Material used for age determination.



Foerster et al., Supplementary Figure 3

Supplementary Figure 3 I Potassium (K) content of Chew Bahir cores CB-01 (basin margin), CB-03 (transition), CB-05 (basin center) for the last 20 ka BP. Dashed lines refers to the African Humid Period (~15–5 kyr BP, AHP), grey bars mark arid phases during the Younger Dryas (YD) and the Older Dryas (OD) stadials as well as during the Last Glacial Maximum (LGM). Age control along the Chew Bahir record is shown by grey squares (radiocarbon ages) and red triangles (CB correlation tie points). The CB records are compared the earth's precession cycle (Berger and Loutre, 1991), lake level fluctuations for Ziway-Shala from Gillespie et al. (1983) and Turkana from Garcin et al. (2012; filled curve), Johnson et al. (1991; dotted curve) and Brown and Fuller (2008; dashed curve). Figure modified after Foerster et al. (2014) and Junginger et al. (2014).

Supplementary Table 1 I Radiocarbon dates from archaeological sites discussed in the text

Site	Fig. Ref[c]	Excavation unit	Cultural complex	Sample ID	Sample material	^{14}C age [yrs BP][a]	Age [cal BP][b]	AMS Conv.	Reference
Main Ethiopian Rift (MER) Lakes									
B1s1	1	Unit XIV	Terminal Pleistocene LSA	Beta-292524	charcoal	11,480 ± 50	13,340 ± 70	AMS	Ménard, C. et al., 2014
B1s1	1	Unit VIII	Terminal Pleistocene LSA	LY-6059	charcoal	11,480 ± 60	13,330 ± 80	AMS	Ménard, C. et al., 2014
DW2s2	2	PS4	Early Holocene LSA	Beta-295898	charcoal	10,040 ± 50	11,560 ±190	AMS	Ménard, C. et al., 2014
DW2s1	2	PS3	Early Holocene LSA	Beta-320183	charcoal	9,830 ± 50	11,250 ± 50	AMS	Ménard, C. et al., 2014
B1s4	1		Terminal Pleistocene LSA	Beta-332588	charcoal	12,040 ± 50	13,900 ± 90	AMS	Ménard, C. et al., 2014
Eth-73-3-III	3		LSA	SMU-86	charcoal	10,330 ± 90	12,190 ± 140	Conv.	Humphreys, 1978
Turkana; eastern shore									
GaJi 3	12	Beach sands Unit B	Fishing settlement	Gx 5475 A	bone (fish)	4,560 ± 185	5,240 ± 280	Conv.	Owen et al., 1982; Barthelme 1985, 131
GaJi1; Nderati Wells	12		Pre-ceramic LSA	Gx 5478	?	13,040 ± 640	15,550 ±1320	Conv.	Mgomezulu, 1981
GaJj 11 [d]	12	Sand bar	Fishing settlement; (pre-pottery LSA?)	Hel-1276	shell	8,920 ± 130	9,920 ± 250	Conv.	Owen et al., 1982
GaJj 11	12	Sand bar	Fishing settlement; (pre-pottery LSA?)	Hel-1277	*Etheria* shell	9,110 ± 130	10,250 ± 230	Conv.	Owen et al., 1982
FxJj 12	13	Sand spits	Fishing settlement; (pre-pottery LSA?)	Gx-5479	shell	9,660 ± 235	11,030 ± 510	Conv.	Owen et al., 1982
FxJj 12	13	Sand spits	Fishing settlement; (pre-pottery LSA?)	R1-954	shell	9,940 ± 260	11,530 ± 600	Conv.	Owen et al., 1982
GaJi 2	12	Beach sands; Lower horizon	Pastoral Neolithic; (cattle bones)	P-2609	charcoal	3,970 ± 60	4,410 ± 110	Conv.	Owen et al., 1982; Barthelme, 1985
GaJi 2	12	Beach sands; Lower horizon	Pastoral Neolithic; (cattle bones)	SUA-634	charcoal	4,160 ± 110	4,680 ± 180	Conv.	Owen et al., 1982; Barthelme, 1985
GaJi 4; Dongodien	12	Beach sands; Unit 5C	Pastoral Neolithic; (cattle bones)	SUA-637	charcoal	3,945 ± 135	4,410 ± 290	Conv.	Owen et al., 1982; Barthelme, 1985, 181
GaJi 4; Dongodien	12	Beach sands; Unit 5C	Pastoral Neolithic; (cattle bones)	SUA-637 B	humic acid	4,100 ± 125	4,550 ± 210	Conv.	Owen et al., 1982; Barthelme, 1985, 181
GaJi 4; Dongodien	12	Beach sands; Unit 5C	Pastoral Neolithic; (cattle bones)	P-2610	charcoal	3,960 ± 60	4,400 ± 110	Conv.	Owen et al., 1982; Barthelme, 1985, 181
GaJi4; Dongodien	12		Pastoral Neolithic; (cattle bones)	Beta-252053	charcoal	4,180 ± 40	4,710 ± 90	AMS	Ashley et al., 2011
GaJi4; Dongodien	12		Pastoral Neolithic (cattle bones)	Beta-252054	charcoal	4,240 ± 40	4,770 ± 70	AMS	Ashley et al., 2011
GaJi4; Dongodien	12		Pastoral Neolithic (cattle bones)	Beta-252056	charcoal	4,180 ± 40	4,710 ± 90	AMS	Ashley et al., 2011
Jarigole GbJj1	14		Pillar site; Pastoral Neolithic	AA85131	OES-bead	4,381 ± 39	4,950 ± 70	AMS	Hildebrand and Grillo, 2012
Jarigole GbJj1	14		Pillar site; Pastoral Neolithic	AA85132	OES-bead	4,251 ± 39	4,780 ± 60	AMS	Hildebrand and Grillo, 2012
Jarigole GbJj1	14		Pillar site; Pastoral Neolithic	AA85133	OES-bead	4,401 ± 39	4,970 ± 80	AMS	Hildebrand and Grillo, 2012
Jarigole GbJj1	14		Pillar site; Pastoral Neolithic	AA85134	OES-bead	4,146 ± 53	4,680 ± 110	AMS	Hildebrand and Grillo, 2012
Il Lokeridede GaJi23	12		Pillar site	TO-4911	charcoal	4,180 ± 60	4,690 ± 110		Koch, 1994; Koch et al., 2002
Turkana; southern shore									
Namoratunga	18		Burial site	GX-5042-A	bone collagen	2,285 ± 165	2,320 ± 290	Conv.	Lynch and Robbins, 1979
Turkana; western shore									
Lopoy	16		LSA „Turkwell“ tradition (pottery)	UCLA 2124J	charcoal	950 ± 80	860 ± 110	Conv.	Lynch and Robbins, 1979
Lopoy	16	Hearth	LSA „Turkwell“ tradition (pottery)	UCLA 2124G	Charcoal	870 ± 80	810 ± 90	Conv.	Lynch and Robbins, 1979
Lothagam North; GeJi9	17		Pillar site	ISGS-A1491	OES-bead	4,385 ± 15	4,940 ± 60	AMS	Hildebrand and Grillo, 2012
Lothagam North; GeJi9	17		Pillar site	ISGS-A1505	OES-bead	4,165 ± 20	4,720 ± 80	AMS	Hildebrand and Grillo, 2012
Lothagam North; GeJi9	17		Pillar site	ISGS-A1492	OES-bead	4,265 ± 15	4,840 ± 20	AMS	Hildebrand and Grillo, 2012
Lothagam West; GeJi10	17		Pillar site	ISGS-A1494	charcoal	4,290 ± 20	4,850 ± 20	AMS	Hildebrand and Grillo, 2012
Kalokol; GcJh3	15		Pillar site	ISGS-A1493	OES-fragment	3,890 ± 15	4,330 ± 60	AMS	Hildebrand and Grillo, 2012
Manemanya; GcJh5	15		Pillar site	ISGS-A1504	OES-bead	4,255 ± 20	4,840 ± 20	AMS	Hildebrand and Grillo, 2012
Manemanya; GcJh5	15		Pillar site	ISGS-A1490	OES-bead	3,805 ± 15	4,190 ± 30	AMS	Hildebrand and Grillo, 2012
Kokito 01; GcJh11	15	Unit A	LSA; (pre-pottery)	ISGS-A1714	charcoal	9,785 ± 35	11,220 ± 30	AMS	Beyin,2011b
Kokito 01; GcJh11	15	Unit A	LSA; (pre-pottery)	ISGS-A1715	charcoal	9,060 ± 30	10,220 ± 30	AMS	Beyin,2011b

South-west Ethiopian Highlands									
Kumali	6	TU3 Level 5B	ceramic LSA	ISGS 5998		1,740 ± 70	1,665 ± 87	Conv.	Hildebrand et al., 2010
Kumali	6	TU4 Level 7	ceramic LSA	ISGS 5999		1,920 ± 70	1,863 ± 85	Conv.	Hildebrand et al., 2010
Kumali	6	TU3 Level 19	LSA	ISGS 6000		4,780 ± 100	5,486 ± 115	Conv.	Hildebrand et al., 2010
Duba	8	TU4 Level 6	LSA	GX 31763		1,840 ± 40	1,781 ± 47	AMS	Hildebrand et al., 2010
Shelui	10	TU2 Level 6	LSA	GX 31762		1,330 ± 80	1,235 ± 75	Conv.	Hildebrand et al., 2010
Koka	9	TU2 Level 15	LSA	GX 31765		2,110 ± 40	2,085 ± 55	AMS	Hildebrand et al., 2010
Koka	9	TU2 Level 20	LSA	GX 31766		2,090 ± 90	2,097 ± 131	Conv.	Hildebrand et al., 2010
Shapa	7	TU1 Level 3	Ceramic LSA	ISGS A1368		970 ± 25	879 ± 45	AMS	Hildebrand et al., 2010
Chiri	11	TU1 Level 3	LSA	ISGS A1366		305 ± 15	372 ± 50	AMS	Hildebrand et al., 2010
Chiri	11	TU1 Level 3	LSA	ISGS A1367		130 ± 100	136 ± 100	AMS	Hildebrand et al., 2010
Mochena Borago[d]	4	H9, Level 5; RCA	LSA	ISGS-6013	charcoal	6,050 ± 110	6,930 ± 190	AMS	unpubl.
Mochena Borago[d]	4			ISGS-6050		7,720 ± 600	8,800 ± 930	AMS	unpubl.
Mochena Borago[d]	4	N42E36, Level 9, HEP	historical	ISGS-A1010	charcoal	135 ± 15	160 ± 100	AMS	unpubl.
Mochena Borago[d]	4	G9, Level 2 RCA	LSA	ISGS-A1011	charcoal	8,440 ± 20	9,480 ± 30	AMS	unpubl.
Mochena Borago[d]	4	TU2S, Level 6 OST	LSA	ISGS-A1012	charcoal	7,055 ± 20	7,890 ± 40	AMS	unpubl.
Mochena Borago[d]	4	C9, Level 10 BWT/MRS	LSA	ISGS-A1532	charcoal	5,760 ± 20	6,560 ± 50	AMS	unpubl.
Mochena Borago[d]	4	C9, Level 11 MRS	LSA	ISGS-A1533	charcoal	4,625 ± 25	5,380 ± 60	AMS	unpubl.
Mochena Borago[d]	4	C9, Level 12 MRS	LSA	ISGS-A1534	charcoal	9,215 ± 35	10,380 ± 90	AMS	unpubl.
Mochena Borago[d]	4	N42E35, Le. 2 ACW	historical	COL-1875	charcoal	166 ± 33	160 ± 100	AMS	unpubl.
Mochena Borago[d]	4	M14, Level 13 ACH	LSA	COL-1876	charcoal	3,942 ± 36	4,390 ± 80	AMS	unpubl.
Mochena Borago	4	G10, hearth1, cutting 5	Ceramic LSA (?)	GIF-11242	charcoal	1,480 ± 80	1,420 ± 90		Gutherz et al., 2002
Mochena Borago	4	Layer 6	Ceramic LSA	GIF-?	charcoal	2,255 ± 80	2,220 ± 110		Gutherz et al., 2002
Mochena Borago	4	Layer 7	Ceramic LSA	GIF-11244	charcoal	2,180 ± 45	2,190 ± 100		Gutherz et al., 2002
Mochena Borago	4	Layer 9, sub-phase 1	LSA	GIF-11246	charcoal	4,370 ± 70	5,060 ± 160		Gutherz et al., 2002
Mochena Borago	4	F2?	Ceramic LSA	?	charcoal	1,915 ± 65	1,860 ± 100		Gutherz et al., 2002
Harouruna	5	Layer 3	LSA	Beta-174905	charcoal	12,070 ± 70	13,930 ± 110	AMS	Bachechi, 2005

[a] Radiocarbon age with 2-sigma standard deviation.

[b] Calibrated radiocarbon ages, mean.

Conventional radiocarbon ages were converted to calendar years using the IntCal13 data set (Reimer et al., 2013) and CalPal (Weniger and Jöris, 2008).

[c] Number refers to archaeological sites as indicated in Figure 1a.

[d] Ages from Mochena Borago are in preparation to be published by S. Brandt, L. Hildebrand, R. Vogelsang and coll.